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State of the Art in 2015 for Calculating the Remaining Strength of Corroded Pipe

Contents

Development of the B31G/RSTRENG and Other Models

B31G

The need for a valid model to assess the remaining strength of corroded pipe became sufficiently urgent in the late 1960s that the pipeline industry through the American Gas Association (AGA) sponsored an effort at Battelle to study the bursting behavior of corroded pipe. Forty-seven full scale burst tests were conducted on samples of pipe containing actual corrosion-caused metal loss, and a variation of Maxey's surface flaw equation[i] that embodied the "Folias factor"[ii] to account for bulging of the corrosion-weakened pipe and "flow stress"[iii] to account for the failure strength of the pipe material was found to give reasonable predictions of the failure stresses[iv].

The advent of in-line inspection (ILI) tools in the 1970s that could locate and characterize the sizes of areas of corrosion-caused metal loss in a buried pipeline encouraged the industry to standardize a method for calculating the remaining strength of corroded pipe based on the dimensions of the metal missing. The model developed previously at Battelle for AGA was embodied in a new standard in 1984: ASME B31G[v].

Modified B31G and RSTRENG

While the B31G model served the purpose for ranking ILI anomalies, its highly simplified and over-conservative treatment of long corrosion on the basis of minimum remaining thickness resulted in large numbers of unneeded excavations. Therefore, AGA once again funded a project at Battelle in 1988 that involved developing a less conservative approach to predicting the remaining strength of corroded pipe. This project[vi] resulted in the development of the Modified B31G model that considers the axial length and depth of the anomaly with no limit on length and an iterative model named RSTRENG that considers the detailed depths of the corrosion within an "effective" length. Additional burst test data acquired mostly from pipeline operators' in-house tests of corroded pipe were added to the database[vii] bringing the total number of tests in the database to 124 not all of which were suitable for analysis by the B31G/RSTRENG approaches (e.g., tests involving brittle fracture initiation, defects aligned in the transverse or diagonal directions, multiple interacting defects, etc. were not used in the evaluation of the models). At this point the B31G-Modified B31G-RSTRENG suite of models had been validated by 86 full scale burst tests.

The Pipeline Research Council International (PRCI) funded additional work in the mid-1990s at Kiefner and Associates, Inc., the objective of which was to enhance the database of corroded pipe tests by including newly acquired data from burst tests on pipes with machined defects[viii]. The total number of burst test results in the database had grown to 216 by this time, 168 of which were suitable for assessing the accuracy of the predictive models. However, the highest grade of material in the database at this time was X65. No data were available to assess the applicability of the B31G/RSTRENG models to higher grades of pipe such as X80 and X100.

In 2009 ASME B31G was revised to include the Modified B31G equation and provisions for more sophisticated analysis of metal loss effects including a description of the "effective area" approach. RSTRENG is an example of an effective area approach. The latest ASME B31G document is a slightly revised version issued in 2012[ix]

Models Other than B31G/RSTRENG

In the meantime other models for assessing the remaining strength of corroded pipe had evolved and were being used by some pipeline operators in place of or in addition to the B31G/RSTRENG models. One of these, LPC-1[x] was embodied in the standard DNV RP-F101[xi]. A second, called PCORR[xii] was developed at Battelle, and the third was called SHELL92[xiii]. The latter is identical to the Level 1[1] assessment model for locally-thinned areas embodied in API RP 579[xiv]. Along with the development of these models, additional burst test data were acquired. In many cases the additional data were generated by testing pipes containing corrosion-simulating machined defects.

Comparisons of the Models to Burst Test Results (the "Advantica" study)

In 2005, the U.S. Department of Transportation (DOT) funded a project with GL Industrial Services UK Ltd (known as Advantica at the outset of the project) to evaluate ASME B31G, Modified B31G, RSTRENG, LPC-1, SHELL92, and PCORR and compare them to the burst test results in the AGA/PRCI database and the additional burst test results acquired in conjunction with the development of the newer models. The results of these evaluations were presented in Reference XV (the Advantica study)[xv]. Failure pressures predicted by each of the six models (denoted as P_f) were compared to actual failure pressures determined in the burst tests (denoted as P_A). The degree of scatter and the bias of the parameter, P_A/P_f, were used to assess the accuracy and inherent conservatism of each model. A database of 313 burst tests was compiled consisting of data from tests conducted by AGA/PRCI tests, GL, Petrobras, the Korean Gas Corporation, the University of Waterloo, and a couple of pipeline operators. Of these 313 results, 133 were obtained through tests of actually corroded pipe, and 180 were obtained through tests of pipe or ring specimens containing machined corrosion-simulating defects. In the case of the pipe specimens, the machined defects had uniform depths and various lengths. In the cases of most of the ring specimens, the machined defects had uniform depths clear across the width of each ring.

The P_A/P_f comparisons for each of the six models were done in six ways called "cases". Case 1 comparisons involved using actual wall thicknesses and material properties and the definitions of flow stress normally associated with each model. Case 1 comparisons served as the measurement of the accuracy of each model. Case 2 comparisons were intended to show model performance in terms of reliably predicting a given factor of safety when used as a means of ranking ILI-detected anomalies. In Case 2 comparisons, nominal wall thickness and specified minimum material properties and the definitions of flow stress for each model were used. Cases 3-6 involved calculations based on various definitions of flow stress and are not as useful for assessing the performance of the models as the Case 1 and Case 2 comparisons.

The Advantica study provides many details on the performance of the six models making it the most thorough compilation of comparisons to date. While it is impractical to discuss all of them

[1] Level 1 models are sometimes called 2-parameter models because they consider only the overall length and maximum depth of an anomaly whereas other models such as RSTRENG and the more sophisticated computer models from which LPC-1 and PCORRC are derived are capable of considering the details of depth along the length of an anomaly. The Level 1 models are essential for analyzing most ILI data because the anomaly listings from the ILI vendor often present only the length, depth, and width of the anomalies.

in this review document, the essence of the findings can be summarized as follows. In terms of scatter the following table shows the frequency distributions of the ratios of actual failure pressures to model-predicted failure pressures for the six models on the basis of the 313 tests. For Case 1 analyses, RSTRENG predictions exhibit the least scatter.

Table 1 Comparisons of Corrosion Assessment Models on the Basis of Burst Test Statistics

Model	P_A/P_f Distribution	
	Mean	Standard Deviation
ASME B31G	1.330	0.468
Modified ASME B31G	1.184	0.285
RSTRENG	1.170	0.177
LPC-1	1.178	0.318
PCORRC	1.191	0.310
SHELL92	1.436	0.407

The original ASME B31G model performed least well in terms of scatter, but Modified ASME B31G exhibited less scatter than four other models Level 1 models.

Models such as B31G and Modified B31G are inappropriate for predicting failure pressures for uniform-depth defects, but as the Case 2 comparisons show, they provide conservative predictions of safe operating pressures when applied with a safety factor of 1.25 or 1.39 to real corrosion defects in materials with specified minimum yield strengths of 70,000 psi or less.

The authors of the Advantica study suggest that further evaluations of the models should be made by conducting burst tests on higher-grade materials (i.e., X80 and X100) using defects that are designed to simulate actual corrosion-caused metal loss rather than uniform-depth machined defects.

The Effects of High Strength on the Performance of Corrosion Assessment Models

With the increasing use of high-strength line pipe (e.g. grades X80 and X100), concern has arisen over possible inadequacies of the current corrosion assessment models (i.e., B31G, Modified B31G, RSTRENG) for analysis of corrosion-caused metal loss in higher grades of line pipe materials. These materials, particularly X100 materials, tend to have yield-strength/tensile-strength (Y/T) ratios in the range 0.93-0.97, low strain hardening capacity and low strain to failure. The high Y/T ratios make the use of the common definitions of flow stress (1.1SMYS for B31G, SMYS + 10,000 psi, for Modified B31G and RSTRENG) for models questionable. Also, the effects of low-strain to failure is thought to be a factor that could affect the applicability of the models.

GL Phase 1 Work: Assessment of Corrosion in Higher Strength Pipe

GL Industrial Services undertook additional work funded jointly be DOT and PRCI known as Project #153H aimed at reviewing the effectiveness of current corrosion assessment models for evaluating corrosion-caused metal loss in higher strength line pipe materials[xvi]. This report was published in August of 2009. The objectives of Phase 1 of this work were to review existing burst test data on higher strength materials to see how well the current models had predicted the actual failure pressures and to see how well a finite-element (FE) model would predict the actual failure pressures.

The finite element (FE) models used in this study are said to be described in Appendix G of BS7910[xvii]. Non-linear, large deformation stress analyses were performed using appropriate software packages. The vessel tests were analyzed using a 3D model, and the ring tests were modeled using a 2D model. Three stages of loading were considered: linear-elastic behavior up to the onset of yielding, yielding spreading through the remaining ligament of the defect, and increasing stress with strain hardening until the von Mises equivalent stress reached the ultimate tensile stress, the latter point being used to define the failure pressure. The failure pressures predicted in this manner were compared to the actual failure pressures of X100 pipe materials (four tests altogether) containing machined, uniform-depth axial grooves or patches and to failure pressures of 10 ring specimens from the X100 pipe materials. The results of the comparisons are described below in conjunction with the comparisons obtained using the current models (i.e., B31G, Modified B31G, RSTRENG, and LPC-1).

Within the database of corroded pipe burst tests reviewed in Reference XV were eight burst tests of X80 pipe samples, four burst tests of X100 pipe samples, and 37 ring tests. In Phase 1 of the actual failure pressures obtained in these tests were compared to the failure pressures predicted by the current models and by the FE analysis.

Four of the eight X80 burst tests were conducted on a material with a diameter-to-thickness (D/t) ratio of 62 and a Y/T ratio of 0.81. The other four X80 burst tests were conducted on a material with a D/t ratio of 82 and a Y/T ratio of 0.80. The Y/T ratios of both of these materials do not seem to represent a low-strain-hardening capability, nor does it seem likely that the definitions of flow stress as 1.1 the actual yield strength or the actual yield strength + 10,000 psi would cause inaccurate predictions. In fact the B31G comparisons were made on the basis of flow stress being defined as 1.1 times the actual yield strength, and the MOD B31G and RSTRENG comparisons were made on the basis of flow stress being defined as the actual yield strength plus 10,000 psi. Machined, uniform-depth, axial grooves were used to simulate corrosion-caused metal loss. The lengths of the defects in the tests were either 3.9 or 4.5 times $\sqrt{Dt}$ meaning that they were "long" defects. Defect depth/thickness ratios ranged from 0.089 to 0.782. The ratios of actual failure pressures, P_A, to predicted failure pressures, P_f, were as follows.

Table 2 Ranges of Ratios of Actual to Predicted Failure Pressures from Tests Done as Part of the GL Phase 1 Work – 8 samples of X80 pipe

	B31G	MOD B31G	RSTRENG	LPC-1
MAX	1.443*	1.195	1.232	1.176
MIN	0.67**	0.745**	1.099	0.993
RANGE	0.773	0.45	0.133	0.183
AVG	1.160625	1.057	1.179625	1.1155

*B31G defaulted to the remaining thickness and infinite length for the 4.5 $\sqrt{Dt}$ cases.
**These low values result because these models consider metal loss areas that are less than the actual areas.

The results indicate that RSTRENG was able to predict the failure pressures with reasonable accuracy using the average of yield strength and ultimate strength as the flow stress. The predictions based on B31G and MOD B31G show what was already known, namely, that these methods are unsuitable for uniform-depth defects.

Four burst tests of an X100 material with D/t of 58, Y/T of 0.98, two with patch defects and two with axial groove defects were carried out. Machined, uniform-depth, axial grooves or patches were used to simulate corrosion-caused metal loss. The lengths of the defects ranged from 3 $\sqrt{Dt}$ to 6.3 $\sqrt{Dt}$. Depths were about 50% of the wall thickness in all four samples. In view of the very high Y/T ratio, one might question whether the normal definitions of flow stress would be adequate. Nevertheless, the B31G comparisons were made on the basis of flow stress being defined as 1.1 times the actual yield strength, and the MOD B31G and RSTRENG comparisons were made on the basis of flow stress being defined as the actual yield strength plus 10,000 psi. The ratios of actual failure pressures, P_A, to predicted failure pressures, P_f, were as follows. Note that the comparisons for FE analysis are included.

Table 3 Ranges of Ratios of Actual to Predicted Failure Pressures from Tests Done as Part of the GL Phase 1 Work – 4 samples of X100 pipe

	B31G	MOD B31G	RSTRENG	LPC-1	Finite Element
MAX	1.175*	1.021	1.136	1.045	1.299
MIN	0.909**	0.897**	1.012	0.96	1.027
RANGE	0.266	0.124	0.124	0.085	0.272
AVG	1.04	0.95925	1.074	1.00125	1.11525

*B31G defaulted to the remaining thickness and infinite length for the cases where the lengths exceeded 4 $\sqrt{Dt}$.
**These low values result because these models consider metal loss areas that are less than the actual areas.

The results indicate that RSTRENG was able to predict the failure pressures with reasonable accuracy using the yield strength plus 10,000 psi ultimate strength as the flow stress. The non-linear FE method gave failure predictions exhibiting more scatter than RSTRENG did.

RSTRENG predictions for 28 of the 37 ring tests gave the following comparisons (P_A/P_f) with actual failure pressures (9 of the comparisons were judged invalid by the GL team):

MAX = 1.237 MIN = 0.931 RANGE = 0.306 AVG = 1.167 STDEV = 0.061

The lowest number was associated with a test involving a notch-like groove that may not have represented corrosion-caused metal loss very well.

The authors of Reference XVI concluded that RSTRENG adequately predicts the failure pressures for corrosion-like defects in higher strength materials such as X80 and X100 even when flow stress is defined as the yield strength plus 10,000 psi. However, they show that more conservative results would result from using the average of yield and ultimate strength as the flow stress. They implied that B31G and Modified B31G may also be adequate for higher strength materials, but that cannot be proven one way or another by means of tests on uniform-depth defects. They suggest conducting tests on higher strength materials with defects created by corrosion-like metal removal methods that would result in defects that look more like actual corrosion defects.

GL Phase 2 Work: Assessment of Corrosion in Higher Strength Pipe

The report on the second phase of Project #153H[xviii] was published in November of 2009. The objectives of the Phase 2 effort were to examine the degree of variation in tensile properties of X100 line pipe across the wall thickness, to examine the differences in tensile properties in the axial and circumferential directions, to conduct two additional burst tests on samples of X100 pipe containing metal loss defects, and to construct failure loci for metal loss in X100 pipe subjected to both circumferential loading (i.e., pressure-induced hoop stress) and externally applied axial loads. In this report it was revealed that parallel efforts were underway at GL as part of Project #153 to evaluate the effects of bi-axial stress, cyclic pressure loading, low toughness, and the interaction of closely spaced defects on the ability to accurately predict failure pressures of corroded pipe using the B31G/RSTRENG suite of assessment methods. It was further revealed that GL was assisting BP in a proprietary operational trial of X100 pipe that included looking at the effects of metal loss on the performance of the pipe. These results of these parallel efforts are reported in separate reports.

Tensile Tests

Tensile tests were conducted on samples removed from X100 DSAW pipes made by three different manufacturers. Two of the pipes were 48-inch-OD (Manufacturers A and B), and one was 52-inch-OD (Manufacturer C). The main objective of these tests was to be able to analyze the effects of biaxial loading on the yielding behavior of X100 materials anticipating that these pipe materials are likely to exhibit non-isotropic yielding behavior. The manufacturers' tests data are shown in the following table.

Table 3 Results of Manufacturers' Tensile Tests on 3 X100 Materials Involved in the GL Phase II Work

Manufacturer		Transverse			Longitudinal		
		Yield Strength, psi	Tensile Strength, psi	Y/T	Yield Strength, psi	Tensile Strength, psi	Y/T
A	Average of three specimens	121,487	130,624	0.93	97,170	126,369	0.77
B	Average of two specimens	108,410	120,302	0.90	93,762	116,749	0.80
C	Average of three specimens	106,114	114,235	0.93	96,493	111,141	0.87

Based on the manufacturers' tests all specimens tested in the transverse (circumferential) direction exhibited yield and tensile strengths that exceeded the minimum requirements of API Specification 5L, 44th edition, for X100 pipe, and the Y/T ratios were 0.93 or less. The yield and tensile strengths measured in the longitudinal tests were all lower than those measured in transverse tests. Most likely the specimens for these tests were flattened strap-tensile specimens.

GL's tensile tests consisted of numerous miniature flat tensile (MFT) tests, standard round bar tensile (ST) tests, and two ring tension tests on each of the three samples of X100 material. The MFT specimens had a thickness of 0.5 mm and a width of 2 mm in the gage section, and ten specimens were obtained through the wall thickness. The intent was to gain insight into the variations in strength through the wall thickness that could be anticipated from the pipe forming process (U-ing and O-ing). Both transverse and longitudinal specimens were created to examine the differences in yielding behavior in those directions. Lastly, samples for the MFT and ST tests were taken from both the 3 o'clock and 6 o'clock positions with respect to the seam weld to examine variations around the circumference of the pipe.

Because of their small size, the MFT specimens had to be created by electro-discharge machining and tested at a special facility. The discussion of the results of these tests suggests that they gave only relative results. Absolute MFT results were inferred by extrapolation from the ST results. The behaviors of the MFT specimens seemed erratic to this reviewer, and might lead one to question their value. According to the authors "There was no identifiable pattern of tensile property variation through the wall thickness." The authors suggested that the MFT specimens probably should have been made twice as thick as they were and that only five specimens should have been created at each location.

The authors state that "From the standard tensile (ST) test results, it was concluded that tensile properties in the longitudinal direction tended to be lower than those in the transverse direction", but not in every case when individual test results are reviewed. When one looks at the stress-strain curves, it looks like there may have been a mix-up in the labeling of the specimens in the two cases where the longitudinal yield strengths appear to have exceeded the transverse yield strengths. The shapes of the curves suggest as much. It would be useful to have the authors consider the possibility that the symbols for transverse and longitudinal may have been accidentally interchanged.

The two ring tensile test samples from the pipes produced by Manufacturers A and B failed after the beginning of yielding but prior to the attainment of 0.5% total elongation as required for a measurement of yield strength. All four of these rings failed at the toe of the DSAW seam. These failures occurred at hoop stress levels above 120,000 psi, so the yield strengths of the base metals in these two pipes exceed the expected minimum level of 100,000 psi. A total elongation of more than 0.5% was attained in each of the two ring tensile tests of the pipe produced by Manufacturer C. The yield strengths exceeded 106,000 psi.

Burst Tests

Two burst tests were conducted on samples of the 52-inch-OD, 0.812-inch-wall X100 pipe supplied by Manufacturer C. The samples contained longitudinally-oriented grooves simulating corrosion-caused metal loss. Both grooves were machined by means of a spherically-shaped tool to a depth of 50% of the wall thickness. The radius of each groove was 0.5 times the wall thickness. The groove in the Test 1 was 79 inches long, and the groove in Test 2 was 29 inches long. The pipes were fabricated with extension pups and end caps and pressurized to failure with water as the test medium. Test 1 ruptured at 1755 psig; Test 2 ruptured at 1987 psig. Both ruptures initiated at the machined grooves.

The authors compared these burst pressures to the predictions of failure pressures of the various models, stating the following results in terms of P_A/P_f ratios. Specified minimum tensile properties were used in each case.

Test Number	ASME B31G	Mod ASME B31G	RSTRENG	LPC-1	SHELL92
1	1.08	0.88	0.97	1.00	1.03
2	1.15	0.88	0.97	0.94	1.01

Similar, though not identical, P_A/P_f values were obtained by this reviewer using KAPA (software that usually gives calculated failure pressures identical to those obtained via RSTRENG).

- ASME B31G: 1755/1718 = 1.02 for Test 1, 1987/2493 = 0.80 for Test 2.
- Modified B31G: 1755/2086 = 0.84 for Test 1, 1987/2250 = 0.88 for Test 2.
- KAPA: 1755/1834 = 0.96 for Test 1, 1987/2015 = 0.99 for Test 2.

Note that the 29-inch flaw of Test 2 is at the boundary limit of $\overline{20Dt}$ where the B31G equation changes to considering the flaw to be parabolic in shape to a flaw with constant depth over an infinite length. For a flaw of 29-inches of less, the parabolic flaw shape is assumed. If one uses the infinite length version, the P_A/P_f ratio for Test 2 via B31G is 1987/1718 = 1.16. The flow stress used in KAPA was taken to be SMYS + 10,000 psi, in other words, 110,000 psi. This would put it very close to the average of the yield and ultimate strengths of the material as measured in the manufacturer's transverse yield and tensile strength tests: 106,114 psi and 114,235 psi, respectively, for an average of 110,174 psi.

The authors acknowledge that Modified B31G cannot be expected to give accurate predictions for uniform-depth flaws because it only considers 85% of the area of the rectangular shape of a uniform-depth flaw of finite length. The authors seem to be implying that the P_A/P_f ratios of near 1.0 given by RESTRENG means that RSTRENG can be used for predicting failure pressures for uniform-depth, blunt flaws in an X100 material.

Analysis of Corroded Pipelines Subjected to Internal Pressure and Secondary Loads

The analysis of the strength of corroded pipe under combined loadings was described in a previous study conducted by GL[xix]. In that study finite element analysis was employed to assess the effects of combined internal pressure and external loading on the failure of corrosion defects in materials of Grades X42 and X65. As stated previously, part of the report being reviewed here was dedicated to extending the analysis to X80 and X100 materials. The stress-strain curves generated by means of the tensile tests described previously were used to facilitate the non-linear, elastic-plastic finite element analysis of corroded pipes under combined stress conditions.

Three-dimensional non-linear finite element models were created to simulate rectangular "patches" of corrosion, axially-oriented grooves, circumferentially-oriented grooves, and isolated spherical pits having depths of 20%, 50%, and 80% of the wall thickness. A "local" failure was deemed to occur when the remaining ligament either "necks" or buckles in response to a given combination of internal pressure and external load. A "global failure was deemed to occur when the von Mises equivalent stress reaches the yield strength of the material. Normalized failure loci diagrams were created for either ratios of applied compressive axial force divided by "critical" compressive axial force or ratios of applied moment divided by "critical" moment versus ratios of applied pressure divided by "critical" pressure of each type-of-defect/defect-depth combination.

The authors recommended that "the normalized failure loci diagrams derived in this report should be incorporated into the PRCI Guidance Document[xx] for assessing corrosion damage in pipelines." The failure loci likely will be used only in special circumstances where a pipeline is subjected to unusual external loads. For most applications criteria such as B31G, Modified B31G, or RSTRENG would be sufficient to assess the remaining strength of corroded pipe. The following quote from Reference XIX helps to put the failure loci in perspective:

"These methods (i.e., B31G, Modified B31G, RSTRENG) were derived based on experimental tests and theoretical/numerical studies of the failure behavior of corroded pipelines subjected only to internal pressure loading. In the vast majority of cases, internal pressure loading will be the main loading mechanism on the pipeline. However, there may be instances when pipelines could also be subjected to significant loading from the environment. For onshore pipelines, these additional loads could be as a result of ground movement due to landslides, mining subsidence, or even seismic activity. In the case of offshore pipelines the formation of free spans may impose significant bending loads. For instance, seabed scour can lead to the development and growth of free spans of pipelines resting on the seabed, particularly if they are not trenched. Whilst, the guidance detailed in standard assessment methods will be sufficient in the majority of cases, it may be inappropriate or non-conservative to use it in cases when the pipeline may also be subjected to significant external loading. The objective of this project is to extend existing methods to allow assessment of corroded pipelines that are subject to both internal pressure and external loading. Development of this new guidance will remove an important area of uncertainty in the assessment methods currently used by the pipeline industry."

Recent Work Sponsored by PRCI on the Assessment of High Strength Pipe affected by Corrosion

Background

PRCI Project EC2-5 was conducted at Battelle[xxi] for the purposes of consolidating data from full-scale burst tests of corroded pipe and using the data to determine whether or not the commonly-used metal-loss assessment equations are consistent across all grades of line pipe from Grade A through Grade X100. The authors refer to high-strength grades of steel as line pipe steels of Grade X70 and up and refer to them by the acronym "HSS" steels or "HSS" pipe. All other materials are referred to as "vintage" materials.

In this report a predictive model for failure stress of a corrosion defect is defined generically as the product of two factors, the first of which is the "reference stress". The reference stress is taken to mean the inherent resistance of the pipe to failure. In the B31G/RSTRENG suite of models, the reference stress is understood to be the flow stress of the material, and flow stress is defined either as 1.1SMYS or SMYS + 10,000 psi. For other models such as LPC-1 and PCORRC, the reference stress is generally assumed to be the ultimate tensile strength of the material.

The second factor represents the effects of pipe geometry and defect geometry. The B31G/Modified B31G models apply a "shape factor" to represent the complex geometry of the typical corrosion defect as a fixed portion of the rectangle formed by the overall length and maximum depth of the defect and a 'bulging factor" to account for the increase in stress in the remaining ligament of pipe resulting from weakening of the shell of the pipe. The shape and bulging effects are accounted for in the LPC-1 and PCORRC models implicitly by one factor determined through finite element analysis.

The authors note that the B31G/RSTRENG models were derived empirically through tests of corroded pipe and pipes containing blunt, corrosion-simulating flaws involving materials from Grade A through X65. They also point out that the LPC-1 and PCORRC models were derived through finite element analyses and validated through test of corroded pipe materials of Grades X42 though X100.

The objectives of Project EC2-5 can be summarized as follows:

1. To assemble a database of tests of vintage pipe and HSS pipe by merging burst test results from the two classes of pipe materials.
2. To identify gaps in the database.
3. To determine whether or not the results of tests on machined flaws should be considered to adequately simulate the results of tests on real corrosion defects.
4. To use the database to show whether or not the various corroded pipe assessment equations give adequate and consistent predictions of failure pressure over the entire database of results.
5. To modify the models as appropriate to assure adequate and consistent predictions.
6. To determine whether or not further full-scale testing was needed to resolve Objectives 2, 3, 4, and 5.

Project EC2-5 consisted of six technical tasks:

i. Gather burst test data on HSS pipe samples with metal loss. Two parts: small pits, high failure stress to examine reference stress trends, and large pits where geometry of the pipe and the defect control failure pressure.
ii. Expanding and restructuring the two parts of the database.
iii. Assessing the role of testing practices.
iv. Full-scale testing.
v. Finite element analysis to assess reference stress for defect-free pipe, "river-bottom/shoulder effect", and flow properties in terms of Y/T.
vi. Assess the corrosion-assessment criteria in terms of margin of safety and grade of pipe. Look for gaps and a means to bridge them.

Discussion of Task 1

In pursuit of Task I, the authors compiled a database of tests on corroded samples and samples containing corrosion-simulating defects that spanned materials from Grade A through Grade X100. They sought test results on samples with large ranges of materials and large ranges of flaw sizes. They suggest that results involving small flaws (sizes trending to zero) would be of help in identifying the unifying definition of reference stress whereas results involving large flaws would tend to be more useful in examining the effects of bulging and shape factors.

Most of the Battelle team's database consists of the "GL R6781 Database" from the "Advantica" study (Reference XV in this reviewer's list). The GL R6781 database contains 313 burst test results, 49 of which were obtained through tests of high-strength steels containing machined, uniform depth flaws. The GL R6871 database is presented in Table A1 in "Annex A" of Battelle's report, and it is identical to the data listed in the Advantica study, Reference XV. It appears the column headings in Battelle' Table A1 labeled "d/t" and "$L\ \ Dt$" have been interchanged. Assuming that to be the case, one can infer that tests with $L\ \ Dt$ values ranging from 146 to 179 are ring-expansion tests whereas the remainder of the tests involved burst tests of end-capped pressure vessels. Index Numbers 248-254 involved 7 ring-expansion tests an X60 material, and thus are not considered HSS materials via Battelle's definition. Index Numbers 255-262 involved 8 pressure-vessel tests of two X80 materials (four tests each). Index Numbers 263-299 involved 37 ring-expansion tests of two X100 materials, and Index Numbers 300-303 involved 4 pressure-vessel tests of an X100 material. The results of the 12 burst tests, 8 involving the X80 materials, and 4 involving the X100 material were discussed previously by this reviewer under the GL Phase I work, Reference XV.

The authors of the Battelle report discuss some "issues" with the database included missing data, missing parameters such as ultimate tensile strength, and the presentation of only D/t ratios as opposed to specific diameters and thicknesses. They also note that details of the testing scope and practices were limited. Apparently GL considered their database proprietary, but they released it "as is" to Battelle under a non-disclosure agreement. Later, many of the missing details were provided to the Battelle team so they could trend the data. The database with these details included is referred to as the GLND R6781 database and is presented in Table A2. Presumably the ND refers to non-disclosable. This database is labeled "confidential".

Battelle is not permitted to distribute the database beyond the member companies of PRCI. There is a gap in Table A2. Index Numbers 230 through 288 are missing.

The Battelle team conducted an extensive literature search to find additional data, but the search yielded no satisfactory data to add to that contained in the GL R6781 database. However, they were able to gain access to the results of 4 full-scale burst tests of high-strength steel pipes containing simulated metal loss defects (referred to as the "Fluxys" tests) and a database of tests of defect-free high-strength steel pipes.

Discussion of Task II

In Task II the Battelle team examined the results of the 49 HSS tests from the GLND R6781 database finding that 37 of them involved ring-expansion tests. They show that the ring-expansion results could have been predicted with a simple net-section collapse analysis because defect length has no meaning in a ring-expansion test. They conclude that the ring-expansion tests are of no value to the overall effort of this project to validate a corroded-pipe analysis method the will be uniform across all grades of pipe. The authors of the Battelle report allude to the absence of a bulging effect because of the absence of the effects of pressure in a ring-expansion test. This depends on whether the ring-expansion test was performed by means of a mechanical expander or by means of actual fluid pressure. The original ring-expansion test was developed by Youngstown Sheet and Tube Company, and it was used by them almost exclusively to determine yield strength only. The tests were never intentionally continued to failure because a failure would damage the testing equipment. Youngstown's ring-expansion tests were carried out via pressurized liquid rather than a mechanical expansion device. If such a device was used by GL, then bulging at the defects could have been present. However, Battelle's decision to eliminate the 37 ring tests from their proposed database is sound. The ring tests offer no means to assess defect length or shape factor.

In the Battelle report the importance of "shape factor" is discussed by noting that Modified B31G (with its shape factor of 0.85) overestimated the results of four burst tests of an X100 material containing uniform-depth defects. It is further noted that if a shape factor of 1.0 instead of 0.85 is used, Modified B31G underestimates the results of the four burst tests.

The 12 pressure vessel tests involving HSS materials in the GL R6781 database, are presented in Table B3 of Appendix B of Battelle's report (Reference XXI). Eight of the 12 tests involved X80 materials, and 4 of the 12 tests involved X100 materials. These tests were discussed previously herein in the Section on the GL Phase 1 work (see Tables 1 and 2). It is recalled that the failure pressures of the 12 tests were conservatively predicted via RSTRENG. It is noted that mistakes appear in Table B3. The values listed for d/t for the X80 materials (the first 8 tests) are the actual depths of the defects, not the d/t ratios. Moreover, the depths given in the d/t column for Tests 7 and 8 are incorrect. In the column labeled (Depth, inches) the values for the first 8 tests are incorrect.

The 12 Fluxys burst tests were carried out on two X70 materials. The results are presented in Table B3 along with those of the 12 results from the HSS materials in the GL R6781 database and 3 tests described below under the discussion of Task IV. In the Fluxys test, four pressure vessels with three defects each were tested. Each of the defects in each vessel were of the same length and depth, but the widths varied from narrow slots to wide patches. In all four vessels, the widest defect failed, and other two did not fail. In effect this means that the Fluxys tests only produced 4 results that can be compared against failure pressure prediction models. So, the actual number of useable results in Table B3 is 19 rather than 27. RSTRENG predictions for the failures are presented later in this review.

The Battelle team suggests that these results show that width does affect the failure pressure contrary to what is normally assumed. It seems that wider defects tend to have lower failure pressures than narrower defects. This reviewer is inclined to agree, although the likely effect, for now at least, has only been documented in tests of uniform-depth machined defects. In fact, a review of the results of certain similar tests in Reference VIII (Index Numbers 119 through 124) showed a similar width effect though at the time it was attributed to unknown factors not related to width. The effect of width could be important, and further work on its effect is in order.

Discussion of Task III

Task 3 of the Battelle study was aimed at examining the effects of test methods and of methods for creating defects on the credibility of the databases assembled under Tasks I and II. The choices of test methods would seem to include burst tests of pipe containing actual corrosion, burst tests of pipe containing artificially-made corrosion, and burst tests of pipe containing machined corrosion-simulating defects. Ring tests as discussed under the Task II work do not produce useful results for the database accumulated by Battelle. The absence of corroded HSS pipe necessitates using machined defects.

The report warns of tests of vessels containing multiple defects, where the effect of pressure cycles on tests of defects that have survived previous test cycles in which more-severe defects had failed can lead to pressure reversals. Indeed, this behavior was observed in some of the earliest testing of vintage corroded pipe at Battelle prior to the development of the B31G criterion. The Battelle team presents additional evidence of such behavior in vintage materials. This threat is said not to be significant with HSS materials based on the premise that the failure mode of plastic collapse is expect for HSS materials. This reviewer would argue that the reverse could be true. That, is the introduction of plastic strain at a near-failure defect in an HSS materials could result in a pressure reversal following the failure of an adjacent defect.

There is speculation in the Battelle report that the behavior of corroded pipe pulled from service is no different from that of pipe containing machined defects if plastic collapse is the failure mode. This is subsequently demonstrated by Battelle's Figure 4 based on the work of Bony, et.al. (Battelle's Refence 26). Their Figure 4 shows that machined defects can legitimately be used as corrosion-simulating defects if the model used to predict failure pressure properly accounts for the shapes of the machined defects and actual metal loss.

The Battelle team uses as their Figure 5, a variation on a figure that was used in the "Continued Validation of RSTRENG", (their Reference 34) to define a "nested" defect, a shorter, deeper pit within a longer, shallower region of metal loss. Such defects can be easily machined and offer a better means than uniform-depth defects for assessing shape factors and the effects of ridges or shoulders that appear with real corrosion where pits overlap. The authors note that RSTRENG is capable of assessing such defects rather well for vintage materials and might do so for HSS materials if the correct reference stress is used. They also note, correctly, the

RSTRENG is not capable of predicting whether a given corrosion anomaly will fail by leaking or by causing a rupture. This, they note, depends on pressurizing medium, toughness, and local defect geometry.

The section of the report on Task III is concluded with the thought that not enough burst test data have been generated with complex flaws especially for HSS materials. They recommend conducting further tests involving shorter features and nested features to strengthen the database and doing an analytical study to assess shape factors.

Discussion of Task IV

Battelle's Task IV efforts on Project EC2-5 consisted of conducting three full-scale tests. The pipe material chosen for these tests was a 30-inch-OD, 0.625-inch-wall, X70M DSAW material with a Charpy V-notch plateau energy exceeding 200 ft lb.

- Vessel One: a round feature 80% through the wall with a diameter of 4.5 inches and a rectangular feature with a length of 10 inches, a width of 6 inches, and a depth of 59% of the wall thickness.
- Vessel Two: a rectangular feature with a length of 6 inches, a width of 3 inches, and a depth of 80% of the wall thickness nested symmetrically within a rectangular feature with a length of 10 inches, a width of 6 inches, and a depth of 45% of the wall thickness.

A lot of thought went into planning the dimensions of the defects. The aim was to have the round feature in Vessel One fail as a leak at about the same pressure that the rectangular feature in the same pipe would fail as a rupture. The compound feature in Vessel Two was designed such that the nested defect would leak. A through-wall flaw failure equation developed on a previous PRCI project (EC2-3) referred to as TW-collapse was used to accomplish this defect- length sizing. PCORRC, a Level 1 corrosion defect assessment model developed previously at Battelle for PRCI, was used to establish the desired surface flaw failure pressures. The three features were created by accelerated corrosion, so the final shapes were not necessarily equal to the target dimensions. However, measurements made after the defects had been fabricated showed that the final dimensions were not far off of the target dimensions. The actual dimensions are given in Appendix C of Battelle's report.

- The failure pressure of round feature in Vessel One was predicted via PCORRC on the basis of target dimensions was 2,590 psig (88.8% of SMYS). The anticipated failure mode was a leak. This defect survived with significant bulging, a pressure level of 2,624 psig (90% of SMYS).
- The failure pressure of the uniform-depth rectangular feature in Vessel One on the basis of the target dimensions was predicted via PCORRC to be 2,601 psig (89.2% of SMYS). The anticipated failure mode was a rupture. The defect failed at a pressure level of 2,624 psig (90% of SMYS) and the failure occurred as a rupture that arrested near the ends of the defect.
- The failure pressure of the compound rectangular feature in Vessel Two on the basis of the target dimensions was predicted via PCORRC to be 2,136 psig (73.2% of SMYS). The anticipated failure mode was a leak within the nested portion. The defect failed at

a pressure level of 2,036 psig (69.8% of SMYS), and the failure occurred as a leak near one end of the nested defect.

The results of 19 of the tests given in Battelle's Table B3 were used to validate the accuracy of PCORRC with regard to predicting failure pressures of corrosion anomalies in HSS pipe materials. The authors imply that PCORRC is more suited than other Level 1 assessment methods to account for the more extreme bulging associated with the failure of a corrosion anomaly in an HSS material. They also note that the one test with the compound (nested) defect demonstrates the "shoulder" effect.

RSTRENG predictions for the 19 tests on HSS materials are presented Figure 1, and PCORRC predictions for 18 of the 19 tests on HSS materials are presented in Figure 2.

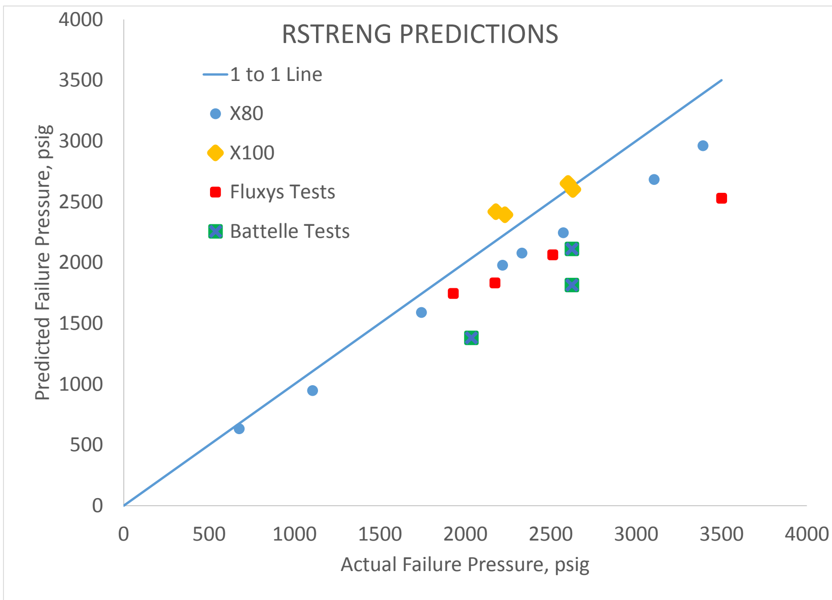

Figure 1 RSTRENG Predictions for the 19 HSS Burst Tests

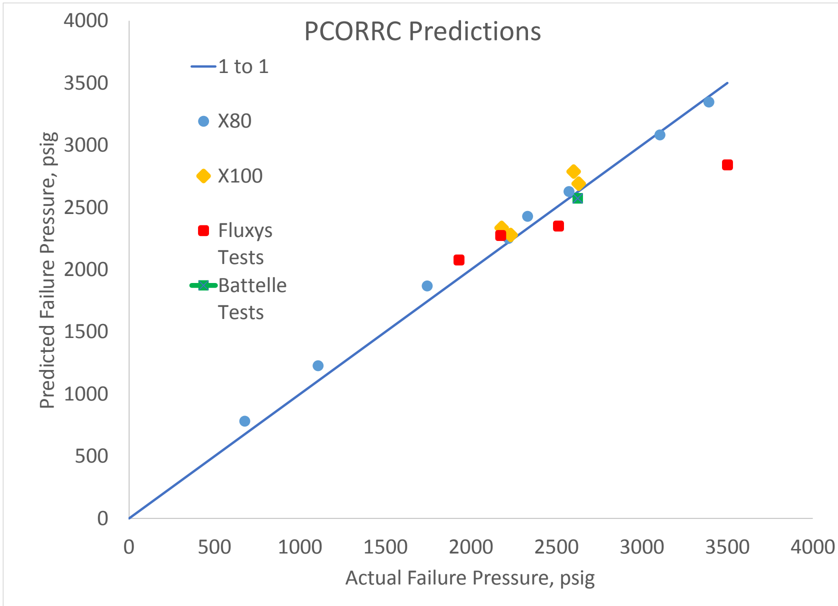

Figure 2 PCORRC Predictions for 18 of the 19 HSS Burst Tests (PCORRC cannot handle the dimensions of the compound defect)

The RSTRENG predictions are based on actual yield strength + 10,000 psi as the reference stress whereas PCORRC predictions are based on ultimate tensile strength as the reference stress. Both models gave reasonably accurate predictions.

The authors assert that the through-wall failure stress prediction model, TW-collapse, is useable to determine whether the failure of a given corrosion anomaly will be a leak or a rupture. The model did well in this role in the three full-scale tests performed by the Battelle team. However, it would be appropriate to test the model against the large numbers of results of tests of actual corroded pipe in the GL R6781 database.

The authors note the complexity of trying to achieve a seamless approach to the assessment of corrosion anomalies across the entire range of HSS pipe materials and vintage pipe materials. They indicate that their Task V analysis is needed to understand how a seamless approach might be achieved.

Discussion of Task V

One objective of Task V of Project EC2-5 was to assess the failure responses of different grades of pipe under plastic collapse conditions so that a single definition of reference stress could be applied to corrosion assessment models. As it stands currently, models such as RSTRENG/B31G utilize a reference stress based on SMYS because that was found to be appropriate for vintage materials. However, models such as PCORR/PCORRC and LPC-1 utilize a reference stress based on the ultimate tensile strength of the material. The latter has been found to be appropriate for HSS materials, and it would be desirable to utilize it across all grades of pipe.

The second objective of Task 5 was to assess the "shoulder" effect of ridges or depth discontinuities between overlapping pits to determine how these features affect bulging and the coalescence of pits that controls failure pressure and whether the resulting failure is a leak of a rupture.

Using their new “Z-L Criterion” based on average shear stress to predict the burst pressures of defect-free pipes of a range of grades from Grade A to X120, the Battelle team showed how ratio of predicted to actual burst pressure varies with yield/tensile (Y/T) ratio. The meaning of the trends they show is that the reference stress used in predicting the failure of corroded pipe varies with the Y/T ratio. They use the concept to suggest that flow stress for vintage materials can be expressed as specified minimum ultimate tensile strength (SMTS) minus 10,800 psi would produce nearly the same predictions with B31G and Modified B31G as would be achieve by using flow stress equal to SMYS + 10,000 psi. They assert that using the SMTS relationship in the RSTRENG/B31G family of models for predicting failure pressures of corrosion anomalies in vintage materials could be a way of achieving a seamless reference stress definition over the range of materials from Grade A through Grade X120.

The Battelle team singles out ultimate tensile strength (UTS) as the parameter that best characterizes the response of defect-free pipe when such pipe is pressurized to failure.

Discussion of Task VI

Summary of the Key Results of Project EC2-5

Summary of Findings on B31G/Mod B31G/RSTRENG

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[i] Eiber, R.J., Maxey, W.A.., Duffy, A.R., and Atterbury, T.J., “Investigation of the Initiation and Extent of Ductile Pipe Rupture”, Report No. BMI-1866, U.S. Atomic Energy Commission Contract No. w-7405-eng-92, NTIS, July 1969

[ii] Folias, E.S., “The Stresses in a Cylindrical Shell Containing an Axial Crack”, Aerospace Research Laboratories, ARL 64-174, (October 1964).

[iii] Hahn, G.T., Sarrate, M., and Rosenfeld, A.R., “Criteria for Crack Extension in Cylindrical Pressure Vessels”, International Journal of Fracture Mechanics, Vol. 5, 1969, pp. 187 – 210.

[iv] Kiefner, J.F., and Duffy, A.R., “Summary of Research to Determine the Strength of Corroded Areas in Line Pipe”, presented at a Public Hearing at the U.S. Department of Transportation, July 20, 1971.

[v] *Manual for Determining the Remaining Strength of Corroded Pipelines*, A Supplement to ASME B31 Code for Pressure Piping, ASME (1984).

[vi] Kiefner, J.F., and Vieth, P.H., “A Modified Criterion for Evaluating the Remaining Strength of Corroded Pipe”, American Gas Association, Catalog No. L51609 (1989).

[vii] Vieth, P. H., and Kiefner, J. F., "Database of Corroded Pipe Tests", American Gas Association (1994).

[viii] Kiefner, J. F., Vieth, P. H., and Roytman, I. "Continued Validation of RSTRENG", PRC International, Catalog No. L51749 (1996).

[ix] *Manual for Determining the Remaining Strength of Corroded Pipelines*, A Supplement to ASME B31 Code for Pressure Piping, ASME (2012).

[x] Fu, B. and Batte, A.D., 'Advanced Methods for the Assessment of Corrosion in Linepipe', UK Health and Safety Executive Summary Report, OTO 1999-051, HSE Books, 1999.

[xi] "Corroded Pipelines", Recommended Practice RP-F101, Det Norske Veritas (1999).

[xii] Stephens, D.R. and Leis, B.N., 'Development of an Alternative Criterion for Residual Strength of Corrosion Defects in Moderate to High Toughness Pipe', Proceedings of the 2000 International Pipeline Conference – Volume 2, Calgary, Alberta, Canada, American Society of Mechanical Engineers, 1-5 October, 2000.

[xiii] Ritchie, D. and Last, S., 'Burst Criteria of Corroded Pipelines – Defect Acceptance Criteria', Paper 32, Proceedings of the EPRG/PRCI 10th Biennial Joint Technical Meeting on Line Pipe Research, Cambridge, UK. 18-21 April 1995.

[xiv] "Fitness-for-Service", American Petroleum Institute Recommended Practice 579, First Edition (January 2000).

[xv] Chauhan, V., and Brister, J., "A Review of Methods for Assessing the Remaining Strength of Corroded Pipelines", GL Industrial Services, Report Number: 6781, Version 6.1 Final Report to U.S. Department of Transportation, November 2009.

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References found at: http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=171

[xvi] Chauhan, V., and Crossley, J., GL Industrial Services UK Ltd., Project #153H: "Corrosion Assessment Guidance for High Strength Steels" (Phase 1), Report Number R9017, to U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, April 2009.

[xvii] Anon: 'Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures', BS 7910:2005, Incorporating Amendment No. 1, BSi, September 2007.

[xviii] Liu, J, Mortimer, L, and Wood, A., "Project #153H Corrosion Assessment Guidance for High Strength Steels (Phase 2)", Report Number: 7930, GL Industrial Services, to: BP Exploration, US DOT PHSMA, Electicore & GL Industrial Services, November, 2009.

[xix] Liu, J., Chauhan, V., Ng, P., Wheat, S., and Hughes, C.,'Project #153J Remaining Strength of Corroded Pipe Under Secondary (Biaxial) Loading', GL Report Number R9068, Issue 2.0, June 2008.

[xx] Fu, B., Jones, C.L. and Chauhan, V., 'Guidance for Assessing the Remaining Strength of Corroded Pipeline', Pipeline Research Council International, Inc., Catalog No. L51958, Advantica Technologies, Inc., August 2002.

[xxi] Leis, B.N., and Zhu, X-K, "Assessing Corrosion Severity for High Strength Steels", Project EC2-5, Prepared for the Corrosion Technical Committee of PRCI, March 13, 2013.